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Effect of attentional interference on balance recovery in older adults

C. Elaine Little and

Department of Human Physiology, University of Oregon, 1240 University of Oregon, 122C
Esslinger Hall, Eugene, OR 97403, USA

Marjorie Woollacott

Department of Human Physiology, University of Oregon, 1240 University of Oregon, 122C
Esslinger Hall, Eugene, OR 97403, USA

C. Elaine Little: elainelit@gmail.com

Abstract

Since most working memory (WM) tasks used in dual-task (DT) postural paradigms include both storage and processing of information, it is difficult to determine the extent to which each of these contributes to interference with balance control. In the current study, a change-detection task (changes in colored squares between two presentation events) that estimates visual working memory capacity (VWMC) was paired with tasks of increasing postural demand (stance, perturbation) in young adults (YAs) and older adults (OAs) and performance compared between the two postural conditions and across the two populations. The change-detection task was selected as it requires storage of information without updating or manipulation; 34 YAs, 34 OAs, and five frail OAs were recruited. A significant reduction in VWMC occurred with increasing postural demand during the perturbation condition for both YAs ($p < 0.01$) and OAs ($p < 0.001$). VWMC was also significantly lower for OAs than YAs in the control condition (1.8 ± 0.7 vs. 2.8 ± 0.6) ($p < 0.001$). OAs showed a significant increase in the number of trials in which steps or rise to toes occurred during recovery between single-task (ST) and DT ($p < 0.05$; $p < 0.05$). OAs also showed a significant increase in normalized tibialis anterior amplitude ($p < 0.001$) following perturbations. YAs showed an increase in normalized area under the center of pressure trajectory and in AP forces (nAcopx1: $p < 0.001$; nFap1: $p < 0.05$) during the DT condition.

Keywords

Postural control; Dual-task postural paradigm; Automatic postural response; Visual working memory; Aging; Fall prevention; Attention

Introduction

The incidence of falling increases with aging, and the adverse effects of falls are broad, ranging from extended hospitalization to death (Tinetti et al. 1988; Alexander et al. 1992).

When balance is disturbed in response to movement of the support surface (e.g., standing on a train or bus during stops and starts) or to an unexpected change in terrain when walking, the nervous system responds automatically to avert a fall. The automatic postural response provides rapid muscle onset latencies that range from 80 to 120 ms and is primarily activated by somatosensory inputs from the ankle and associated muscles (Nashner and Berthoz 1978).

Select research shows that cerebral cortex and high-level cognitive processing also contribute to aspects of balance control and that postural performance deteriorates in some dual-task (DT) (performing two tasks at once) contexts (Lajoie et al. 1993; Rankin et al. 2000; Woollacott and Vander Velde 2008). Information processing resources are thought to be limited, and thus, competition between two attentionally demanding tasks may lead to task interference. It has been postulated that if two tasks performed simultaneously require more than the total attentional capacity, the performance on one or both tasks will be affected negatively (Kahneman 1973; Wickens 1983).

A variety of cognitive tasks have been reported to interfere with postural control, including auditory reaction time (RT) tasks (Lajoie et al. 1993; Brauer et al. 2001), executive function tasks, including counting backward by 3 s (Brown et al. 1999), auditory or visual N-back tasks (Huxhold et al. 2006; Dumas et al. 2008), the auditory Stroop task (Siu et al. 2008), and a variety of motor tasks (Hadjistavropoulos et al. 2012; Cluff et al. 2010). Thus, visual interference is not required to produce reductions in postural or cognitive performance in DT contexts. It has previously been shown that an auditory RT task (saying the word “high” or “low” to a high or low tone) significantly increased the time required to recover from a platform perturbation and decreased the amplitude of muscle responses used to respond to the perturbation in older adults (OAs) (Brauer et al. 2001). Thus, a key factor contributing to DT interference may be the information processing required, rather than a specific sensory channel that is used by both tasks, thus creating a bottleneck. Not all of the postural DT research, however, shows interference in the performance of postural and cognitive tasks under dual conditions (Dault et al. 2001; Norrie et al. 2002). Some authors have suggested that this was due to different levels of difficulty used for one or both tasks, while others proposed that it was due to the nature of the cognitive resource targeted during the tasks (Logie et al. 1990; Cocchini et al. 2002).

Many studies using DT paradigms to examine balance use a working memory (WM) task as the cognitive task (Lajoie et al. 1993; Huxhold et al. 2006; Woollacott and Vander Velde 2008). Most WM tasks involve both information storage and processing with the majority requiring the preservation of information while concurrently processing the same or other information (e.g., reading span tasks, counting span tasks, verbal response to auditory stimuli, the N-back task or the Brooks’ spatial memory task (Lajoie et al. 1993; Huxhold et al. 2006; Quinn 1994). Neural imaging techniques have shown that brain activation areas differ during processing associated with varying WM tasks (Collette et al. 2005; Logie et al. 2011). Thus, the use of different neural networks may also be a factor contributing to variability in results seen in the DT postural control literature for young adults (YAs) and OAs (Dault et al. 2001; Woollacott and Vander Velde 2008; Norrie et al. 2002; Lajoie et al. 1993; Shumway-Cook et al. 1997; Brauer et al. 2001).

We posited that pairing a visual working memory (VWM) task, shown to involve retention or storage of information in isolation, would provide clarity concerning interference between tasks requiring simultaneous control of posture and VWM. Work by McCollough et al. (2007) indicated the change-detection task (detecting changes in colored squares between two presentation events) used only temporary retention (storage) of visual information with no updating or manipulation; thus, it was selected for use in this study. Results from studies that have used the change-detection task to probe VWM capacity converge, suggesting a fixed limited capacity (defined as the number of unique items held in WM, which has been determined to be 3–4 in YAs) (Luck and Vogel 1997; Vogel and Machizawa 2004; Pashler 1988). In addition, performance does not appear to be influenced by perceptual processes (Sperling 1960). An interference pattern between the storage of information associated with the change-detection task and postural control has been established in YAs (Little 2012).

The focus of the current paper was to evaluate and compare postural control and VWM capacity under single-task (ST) and DT conditions between YAs and OAs. The change-detection task was paired with tasks of varying postural demand. Four hypotheses were addressed: (1) There would be a decline in VWM capacity for both YAs and OAs as postural challenge increased, (2) OAs would demonstrate a significant reduction in VWM capacity (control) as compared to YAs (with set sizes of 2, 4, and 6), (3) EMG amplitudes would be reduced among OAs during the automatic postural response of the DT condition, and (4) OAs would show significant increases in alternate strategies for postural recovery.

Materials and methods

Participants

Thirty-four YAs (aged 19–24 years; mean age, height, and mass: 20.6 ± 1.5 , 170.8 ± 9.5 cm and 70.2 ± 11.4 kg, respectively) were recruited for the study to provide a baseline reference for cognitive and automatic postural performance under ST and DT conditions in the current experimental paradigm. Two OA groups were included based on their level of physical function, which was established using the Fullerton Advanced Balance Scale (FAB). The FAB scale is a predictive measure of faller status when used with independently functioning OAs; individuals who score ≥ 25 have been shown to be at high risk of a fall (Hernandez and Rose 2008). Thirty-four OAs, not at risk of falling (65–77 years; mean age, height and mass: 71.8 ± 4.1 , 164.0 ± 8.1 cm, 74 ± 9 kg, respectively), and five OAs at risk of falling, referred to as frail OAs (70–90 yrs; mean age, height, mass: 81.4 ± 8.2 , 161.8 ± 3.8 cm, 67.6 ± 14.7 kg, respectively), were recruited for the study. Frail OAs were recruited to help shed light on whether any differences in behavioral postural performance could be revealed across a broad spectrum, YAs versus OAs versus frail OAs.

Neuropsychological tests were used to evaluate executive function skills, specifically the Trail Making Test (TMT) Parts A and B and the Mini-Mental State Examination (MMSE) (Folstein et al. 1975; Arbuthnott and Frank 2000; Bugalho and Veana-Baptista 2013). The MMSE, used to screen for dementia, was administered solely to the OAs (see Table 1). Inclusion/exclusion criteria included: living independently, no recent sprains, broken bones or musculoskeletal disorders, no neurological disorders (stroke, paralysis, or numbness), no peripheral sensory changes associated with diabetes, able to stand for 30 min intervals

unaided, (e.g., no walker or cane), and no absence or decline in short-term memory. Young adults were included who had no history of concussion or mild traumatic brain injury (mTBI), and both YAs and OAs were excluded if taking medication known to affect postural control or cognitive function. Each participant was informed of experimental conditions and gave written consent prior to initiating the testing session. All procedures were approved by the office for protection of human subjects at the University of Oregon.

Protocol

Cognitive task

The change-detection task was used to establish a value for VWM capacity. During the initial consolidation/encoding phase, memory arrays of 2, 4, or 6 squares were viewed for 500 ms, followed by a blank gray screen with a central cross (distance of 70 cm), during which subjects retained in memory the number, position, and color of the array for 900 ms. During the final 2,000 ms retrieval phase, a test array was presented and subjects indicated whether memory and test arrays were identical or different using bilateral button presses (left—no change, right—change).

Each set of squares was presented 30 times for a total of 90 trials, with a practice session preceding experimental conditions to eliminate learning effects. Some OAs required 2–3 repetitions of the practice session before becoming proficient with the cognitive task. An algorithm randomly selected from a set of seven colors; colors appeared no more than twice within an array. Stimulus positions were randomized on each trial, with the constraint that the distance between squares was at least 2° (center-to-center). The color of one square was different in half of the test arrays. Figure 1a shows an OA performing the task while standing. Figure 1b presents examples of possible colored square configurations.

Postural conditions

Postural conditions included the control (sitting), isolated stance, “expectation” (isolated stance intermixed with perturbations), and perturbation of the support surface. The term “expectation” signifies the isolated stance intermixed with perturbations condition, because subjects knew perturbations would occur at random intervals. The isolated stance and perturbation conditions were evaluated under both ST and DT conditions. Memory capacity obtained during sitting was the control condition for the cognitive task.

Participants were instructed to select a comfortable stance position that was traced on the force plates and were asked to maintain a neutral posture; if subjects stepped, they were instructed to resume the initial position. No constraint was placed on subjects to maintain neutral posture without moving their feet. In DT conditions, they were instructed to focus equal attention on the postural task and the VWM task. To eliminate the habituation of responses to the perturbation, the time between perturbations was randomized (8–15 s). Change-detection task trials, ranging from 10 to 20 trials, continued between backward and intermittent forward perturbation trials of the support surface. This resulted in an increased number of change-detection task trials during the “expectation” condition (Table 2). Adding forward perturbations reduced subjects’ tendency to prepare for a perturbation by leaning

backward in order to reduce forward sway; it thus promoted a neutral upright stance between support surface perturbations.

In the DT condition, platform movement immediately followed presentation of the 500 ms memory array, coinciding with the beginning of the retention interval, for a total of 90 perturbations. Table 2 summarizes the experimental protocol including trials used to determine behavioral performance of the cognitive task and postural task. Trials used to compare characteristics of postural responses between ST and DT conditions were also included. To ensure visual demands were kept constant between the two conditions, subjects focused on a cross projected on the monitor during ST conditions. Subjects manually depressed buttons randomly during the ST condition, to keep any additional motor requirements constant across both tasks. The experimental design was balanced to ensure condition order did not confound WM task performance: equal number of subjects performed the following sequences: sit–stand–perturbation, perturbation–sit–stand, and stand–perturbation–sit. Subjects wore a safety harness to prevent falls during the perturbations.

Data collection

Recorded data included ground reaction forces (GRFs), electromyography (EMG), and force plate position sampled at 1,000 Hz using a Motion Analysis Acquisition Unit (12 bit A/D inputs with a ± 5 V range and amplifier with a gain of 10—resolution 2.441 mV/bit). GRFs and plate position were obtained using a platform system built by the Institute of Neuroscience Technology Group at the University of Oregon: amplitude of the displacement of 10 cm with a peak velocity of 30 cm/s, a duration of 0.5 s, and acceleration of 0.34 m/s/s. Raw EMG was amplified through a preamplifier, DC Power Supply ± 5 V at 2.5 mA, with an input impedance greater than 100 M Ω using pairs of bipolar surface electrodes (disposable blue sensor, silver–silver chloride, Medicotest, Inc.) with an inter-electrode distance of 2 cm. The following muscles were recorded bilaterally: tibialis anterior (TA), gastrocnemius (GA), rectus femoris (RF), hamstrings (HA), and erector spinae (ES) at L_{4–5}. Kinematic data were obtained using 31 reflective markers secured to bony landmarks and the force plates; their positions (x , y , z coordinates) were tracked by a 10 camera (infrared) system (resolution 1 mm), sampled at 100 Hz. Data related to stepping were only behavioral in nature. The number of trials in which an individual took a step(s) as part of ST and DT recovery was noted. Steps were identified by visual observation using the following criteria: one or two feet moved from the original selected position forward, backward, to the side, or when one foot was lifted from its original position in response to the perturbation.

Data analysis

Postural variables

The number of trials in which individuals took a step during the 21 ST trials (4–14 and 117–126) was compared with the 90 DT trials (15–116). To analyze postural variables (forces and EMG), means from trials 10–14 (ST) were compared with trials 15–19 (DT). If steps were taken during any of the trials typically included in the ST or DT trial sets, alternative trials directly preceding or following were used, to include five trials per trial set. Stepping

trials were not included in the overall analysis of postural variables, as distinctly different force and neuromuscular response strategies are used for taking steps versus using an in place strategy to recover balance. The postural data were subdivided in this manner to separate the DT effect between ST and DT conditions from any attenuation of postural responses which could occur following repeated application of the same stimulus (Horak and Nashner 1986; Macpherson et al. 1989).

Vertical GRFs were combined bilaterally to characterize the trajectory of the center of pressure (COP) along the anterior–posterior (A–P) axis. The COP data were low-pass-filtered at a cutoff frequency of 50 Hz and re-sampled at 100 Hz. The area under the COP trajectory along the A–P-axis was quantified in mm–ms for two consecutive bin widths of 80 ms (YA: 190–270 and 270–350 ms following onset of platform movement; OA 200–280 and 280–360 ms) plus 100 ms of estimated excitation–contraction coupling time. Onset latencies selected were based on mean onset latencies from gastrocnemius (GA) for the ST condition from a subset of Y and OAs (onsets of 93 ± 10 and 102 ± 7 ms, respectively), which fall within the range identified in previous studies (Horak and Nashner 1986; Woollacott et al. 1986). Criteria used for onsets were three SD above baseline activity (200 ms preceding perturbation) sustained for 50 ms. Area under the A–P force trajectory, in N–ms, was also quantified for the same two bins.

The EMG data were high-pass-filtered (cutoff frequency of 10 Hz), then full-wave-rectified, and low-pass-filtered (cutoff frequency of 35 Hz). Right and left muscle EMG traces were averaged. EMG responses were quantified by area under the EMG curve (mV–ms) for two bins of 80 ms width (90–170 and 170–250 ms for YAs; 100–180 and 180–260 ms for OAs). The two time bins captured events occurring during the early (bin 1) versus late (bin 2) phase of the automatic postural response (Horak et al. 1989).

Cognitive measures

An equation developed by Pashler (1988) was used to estimate the number of items (K) that can be maintained in WM, $K = SS (HR + CR - 1)$, where SS = set size (2, 4, or 6), HR = hit rate (number of times the change in squares was correctly identified), and CR = correct rejection (number of times no change in squares was correctly identified). Working memory capacity was calculated for the 30 trials of each set size and used to calculate the average K for the 90 trials by summing the set size K -scores and dividing the total by 3 (details in Table 2).

Statistical analysis

Since WM capacity demonstrated high variability among all the measures, it was used as the sample size determinant; an alpha level of 0.05 was used, and based on an expected drop in K of 0.2 and an approximate standard deviation of 0.35, an effect size of 0.6 was predicted at a power level of 90 % (Norman and Streiner 2000). To facilitate across-subject comparisons, variables were normalized to the absolute value of the mean from five trials of the SB trial set of bin 1 for all trials, Copx-bin 1&2, APforce-bin 1&2, and GA-bin 1&2, with the following exception. Because two muscles exhibited low-amplitude responses in bin 1 compared with bin 2 (resulting in inflation of the values in bin 2), the EMG areas of TA,

HA, RF, and ES were normalized to the absolute value of the mean from five trials of the SB trial set of bin 2.

Dependent variables associated with behavioral performance included VWM capacity (K), Fullerton Advanced Balance (FAB) Scale scores, the number of trials in which subjects' stepped, and the number of trials in which rise to toes was used as part of the recovery strategy. This behavioral variable was added after EMG analysis identified a significant increase in TA activation in DT compared with ST conditions in OAs, as TA activation is not typical with a posterior perturbation of the support surface. A subset of the data was used to establish whether OAs used a rise to toes strategy during postural recovery. The data were subdivided into five trial sets (trials 10–14 and 117–121 represented ST performance, and trials 15–19, 60–65, and 112–116 represented DT performance). Rise to toes was defined as a change in vertical heel position of 30 + mm compared with quiet stance, determined from kinematic data. This value was chosen to account for reductions in range of motion and general strength observed with aging (Mecagni et al. 2000; Spirduso et al. 2005). The dependent postural variables included normalized area under the COP trajectory in the AP axis (nAcopx), normalized area under the A–P force trajectory (nFap), normalized EMG amplitudes (nGA, nHA, nES, nTA, and nRF) for both bin 1 and bin 2.

The statistical package, SPSS was used for analysis (Field 2009). Due to technical difficulties resulting in missing data from one male, data from 33 YAs and 30 OAs were included in the statistical analysis associated with the automatic postural response. Four healthy OAs (two females; two males) were excluded from the statistical analysis of the automatic postural measures due to lack of data in the ST condition. These subjects had an increased frequency of stepping during the ST condition (subjects feet must remain in contact with the force plate to generate measureable data); once they adapted to the perturbation, the number of step trials was greatly reduced, but the lack of ST data prevented comparison with the DT condition in these individuals. Data from the five frail OAs were excluded from statistical analysis of the behavioral cognitive measure, and the automatic postural response measures analysis due to low sample size, and behavioral postural response alone (the number of trials in which individuals took a step) was presented in the current study.

The study was a repeated-measures design. Significance level was set to p values less than $p = 0.05$. An effect size of 0.1 was considered small, 0.3 moderate, and 0.5 large (Field 2009). A mixed one-way repeated-measures analysis of variance (ANOVA) was used to analyze the effects of postural condition (Sitting, Stance, "Expectation", and Perturbation) on VWM capacity as within factors, across age groups (YAs vs. OAs) as between factors. A mixed one-way ANOVA was used to analyze the drop in K (sit vs. "expectation" and sit vs. perturbation) as within factors across age groups as between factors. Independent t test was used to compare K in the control (sitting) condition between YAs and OAs.

A mixed two-way repeated-measures ANOVA was used to analyze the effects of condition (ST vs. DT) by postural measures as within factors, across age groups (YAs vs. OAs) as between factors. A mixed one-way repeated-measures ANOVA was used to analyze the effect of condition (ST vs. DT) on behavioral postural measures as within factors, across age

groups (YAs vs. OAs) as between factors. Separate post hoc Bonferroni corrections analysis or repeated contrasts were specified a priori as appropriate to the measures examined between test conditions for YAs and OAs when the first stage of analysis revealed significant interactions. Pearson's correlation was used to determine whether there was a relationship between (1) DT-TA1 activation and a rise to toes difference score between DT and ST conditions in OAs and (2) whether a relationship existed between the number of steps taken in the DT condition and the drop in K (Perturbation minus Sitting).

Results

Dual-task effects

Cognitive: visual working memory capacity—A significant postural condition (Sitting, Stance, “Expectation,” and Perturbation) by age (YAs vs. OAs) interaction was observed for VWM capacity (K -scores), $F(3,64) = 3.451$, $p < 0.05$, $r = 0.23$. This suggested that the modulation of VWM capacity across postural conditions differed between YAs and OAs. Post hoc Bonferroni corrections revealed a significant decrease in K between the control and perturbation conditions ($p < 0.01$) in YAs. However, YAs showed no significant difference in K between the control and stance conditions ($p < 1.000$), the control and “expectation” conditions ($p < 0.071$), the stance and “expectation” conditions ($p < 1.000$), or the “expectation” and perturbation conditions ($p < 0.377$). In OAs, a significant decrease in K was seen between the control and perturbation conditions ($p < 0.001$), the control and stance conditions ($p < 0.05$), and the “expectation” and perturbation conditions ($p < 0.01$). No significant difference was seen in K between the control and “expectation” conditions ($p < 0.392$) or the stance and “expectation” conditions ($p < 0.206$) in OAs. The inverse relationship between VWM capacity and postural conditions for both Y and OAs is shown in Fig. 2a. The magnitude of the difference in K between ST (sitting) and DT (perturbation) conditions was greatest in the OAs as compared to the YAs (Fig. 2a). A significant interaction was seen between drop in K and age, $F(1,66) = 6.596$, $p < 0.05$, $r = 0.3$, which suggested that the drop in K between conditions differed in YAs and OAs. A priori repeated contrasts revealed that the drop in K between sit and “expectation,” and sit and perturbation was significantly greater in OAs ($F(1,33) = 16.44$, $p < 0.001$, $r = 0.6$) but not in YAs ($F(91,33) = 3.707$, $p < 0.063$) (Fig. 2b).

The independent t test showed a significantly lower VWM capacity in the control condition ($t(33) = 5.84$, $p < 0.001$, $r = 0.71$) in OAs compared with YAs. The average VWM capacity for YAs in the control condition was 3 (2.8 ± 0.6) as compared to 2 (1.8 ± 0.7) for OAs, an approximate difference of 40 %. This result supports our hypothesis of an overall decline in VWM capacity with aging and replicates results of Jost et al. (2011).

Postural measures

A significant three-way interaction between postural measures, condition (ST vs. DT), and age group (YAs vs. OAs) was observed $F(3,286) = 3.021$, $p < 0.05$, $r = 0.10$. This suggested there was a DT effect in the postural recovery response that differed between YAs and OAs. Post hoc Bonferroni corrections revealed a significant increase in nAcopx1 ($p < 0.01$) and nFap1 ($p < 0.05$) between DT and ST conditions, but no difference in nAcopx2 ($p < 1.000$)

or nFap2 ($p < 0.587$) in YAs. Furthermore, YAs showed a significant increase in EMG activation between ST and DT conditions in one muscle, ES1 ($p < 0.01$) with no difference in any of the others analyzed: nTA1 ($p < 0.106$), nGA1 ($p < 0.130$), nRF1 ($p < 0.314$), nHA1 (0.148), nTA2 ($p < 0.098$), nGA2 ($p < 1.000$), nRF2 ($p < 0.427$), nHA2 ($p < 0.146$), or nES2 ($p < 0.083$).

As expected, postural response patterns differed between YAs and OAs. Bonferroni corrections revealed no significant difference in nAcopx1 ($p < 0.202$), nFap1 ($p < 0.587$), nAcopx2 ($p < 0.355$), or nFap2 ($p < 0.076$) for OAs in the DT compared with ST conditions. However, OAs showed a significant increase in EMG activation between ST and DT conditions in the following: nTA1 ($p < 0.001$), nHA1 ($p < 0.05$), nRF2 ($p < 0.001$), nHA2 ($p < 0.001$), and nES2 ($p < 0.001$). No significant DT effect was seen in OAs for any of the other EMG analyzed: nGA1 ($p < 0.822$), nRF1 ($p < 0.070$), nES1 ($p < 1.000$), nTA2 ($p < 0.065$), and nGA2 ($p < 1.000$).

The number of trials in which subjects used rise to toes as part of the postural strategy was examined to account for the unexpected result of a significant increase in TA1 activation in the DT condition in OAs. There was a significant interaction between condition (ST vs. DT) on postural behavioral response and age group, $F(1,61) = 6.053$, $p < 0.05$, $r = 0.30$. This suggested that there was a DT effect on postural behavioral responses, which differed between YAs and OAs. A priori repeated contrasts revealed a significant increase in the number of trials in which OAs used rise to toes ($F(1,29) = 5.370$, $p < 0.05$, $r = 0.40$) and in the number of trials in which a step was taken ($F(1,29) = 5.734$, $p < 0.05$, $r = 0.40$) between ST and DT conditions. No significant difference was seen between ST and DT in YAs (rise to toes trials: $F(1,32) = 1.721$, $p < 0.199$; step trials: $F(1,32) = 1.902$, $p < 0.177$).

Those individuals who took a step in various trials did not necessarily rise to toes in the same number of trials. Table 3 provides a summary of the number of subjects who either used rise to toes or stepped as part of their postural recovery pattern in the experimental paradigm. There was a trend ($r^2 = 0.120$, $p = 0.06$) toward correlation between DT-TA1 activation and the increase in rise to toes (DT – ST) in OAs. No correlation was seen, however, between the stepping trials in the DT condition and the drop in K between ST cognitive (Sitting) and the DT cognitive conditions (cognitive plus perturbation). Figure 3a presents the mean number of trials with steps in YAs and OAs, and 3 b compares OAs to the five frail OAs who were recruited for the study. Figure 4 shows that there was a significant increase in the number of trials in which rise to toes was used as part of the postural recovery pattern in the DT compared to the ST condition in OAs but not YAs.

Discussion

The goal of the present study was to determine the interaction between VWM and the automatic control of posture in Y and OAs under DT conditions. The advantage of the VWM task used in this study is that it targets an isolated attentional resource and does not require further processing beyond recognition, and storage of color and position of simple squares. The measure of memory capacity, K , allowed us to quantify the upper limit of performance for this cognitive task. Any reduction in K is, therefore, interpreted as an indication of

competition related to the change in conditions. The variety of postural conditions allowed us to sample a wide range of balance challenges from independent stance to the response to a sudden, very challenging perturbation. The latter task was designed to force the central nervous system (CNS) to work optimally, such that any decrement in the ability to perform the postural task would be evident in our postural measures.

A decline in VWM capacity was seen as postural demand increased, with a significant reduction in K in the perturbation condition (automatic postural response) for both Y and OAs. Based on the fact that OAs demonstrated a lower baseline VWM capacity (K) compared with YAs, it is not surprising that the greatest reduction during perturbation was seen in OAs. OAs also showed a significant increase in the number of trials in which they took a step to recover balance during the DT compared with the ST condition. Although the number of frail OAs, who participated in the study, was insufficient to include in the statistical analysis, Fig. 3b shows that the number of trails in which steps were taken was markedly increased in the frail OAs in both the ST and DT conditions as compared to the healthy OAs. For analysis of forces and EMGs used in postural recovery, we eliminated those trials in which individuals took a step; thus, any changes we have seen in force and EMG response characteristics between O and YAs are a conservative estimate.

Salthouse (1994) has made a strong case for the contribution of a generalized age-related slowing in processing speed to many adult age differences in cognition. However, other authors have provided evidence that not all task impairment is due to slowing. For example, when the orienting network of attention was evaluated with the use of the Attentional Network Task (ANT), OAs benefitted as much as YAs from peripheral cues (Jennings et al. 2007; Folk and Hoyer 1992). Orienting was not affected by age-related slowing even when cues were presented for as little as 100 ms (Jennings et al. 2007). Using a change-detection task, similar to the paradigm of the current study, Jost et al. (2011) found that age-dependent drop in K was coincident with reduced filtering scores; this is consistent with the inhibition-deficit theory (Hasher and Zacks 1988) which maintains that as we age our ability to suppress irrelevant representations or response tendencies declines. Jost et al. (2011) found that age-related delay in filtering was not accompanied by a general delay in WM encoding even with a presentation time of 200 ms, 300 ms shorter than the 500 ms used in the current study. Thus, the drop in K seen in the current study reflects the interference pattern between the two modalities, cognitive processing and the automatic postural response.

Furthermore, Jost et al. (2011) evaluated a broad range of set sizes, which demonstrated the importance of including larger set sizes within the change-detection experimental paradigm to provide the best estimate of K . Performance of YAs and OAs was near ceiling and did not differ significantly with set size of one item. The estimation from the set size of three, revealed a capacity of 1.46 items for OAs and 2.14 for YAs but this can be an underestimate of capacity, as mathematically K can never exceed the number of the to-be-stored items, in this case 3. For example, if an individual with a VWM capacity of five was tested with set size of three, the individual's VWM capacity would be 3, which would be an underestimation. When capacity was established with a task in which up to eight items had to be maintained YAs were estimated at 2.99 items (similar to previous studies, e.g., Vogel

and Machizawa 2004) and for OAs 2.05 items. Thus, six items were included in the current experimental paradigm to avoid ceiling effects.

The use of different postural strategies observed in the current study between YAs and OAs helps to elucidate the effects of aging on stability. Pai et al. (2000) has shown that it is the interaction between center of mass (COM) position, and its velocity that influences whether a person will be able to remain stable within their base of support (BOS) or be required to take a step in order to regain stability in dynamic conditions such as recovery from a perturbation. Although both YAs and OAs stepped periodically across the 115 trials during postural recovery in the current study, OAs showed a significant increase in the number of trials in which they stepped between ST and DT conditions. Loss of spinal flexibility in OAs can contribute to a compensatory shift in COM position backward toward the heels within the BOS (Shumway-Cook and Woollacott 2012). Thus, altered COM position and/or ability to control COM velocity may influence the strategies used to maintain or regain stability.

Even though subjects were not told to keep their feet in the starting position to maintain neutral posture, rise to toes was also seen as part of the recovery strategy in YAs and OAs. When population statistics were compared OAs showed a significant increase in rise to toes trials between ST and DT conditions. The research paradigm was designed to push subjects near to their limits of stability such that the CNS would be forced to work optimally. Our results show that YAs were able to remain stable within their BOS with the use of an ankle, or hip, or combination of ankle and hip strategies. In addition to these strategies, OAs used rise to toes as part of the in place recovery strategy to remain stable within their initial BOS and/or took a step to regain stability when they were unable to keep the COM from traveling outside the BOS.

Given the nature of the postural disturbance, the significant increase in TA1 activity was unexpected in OAs. When combined with the significant increase in rise to toes trials seen in OAs, these results are similar to research that demonstrated increased TA activation during the active switch from a foot flat position to an up-on-toes position (Nardone and Schieppati 1988). The muscles in this work included only TA and GA; thus, it is not clear whether activation of HA1, RF2, HA2, and ES2 seen in the current study was also part of the pattern associated with active rise to toes. The up-on-toes position produced a backward displacement of the COP, which may account for the lack of a significant increase in nAcopx (bin 1 and 2) in the OAs between ST and DT conditions (Clement et al. 1984; Nardone and Schieppati 1988).

The greater decline in VWM capacity in OAs compared with YAs, along with the strategy changes associated with the postural task suggests that OAs have a reduced level of attentional capacity, which puts this group at a greater disadvantage when trying to perform cognitive and balance tasks simultaneously.

Our results differ from the Rankin et al. (2000) study that paired backward perturbations of the support surface with a cognitive task. They reported a reduction in GA and TA amplitudes late in the recovery phase, 350–500 ms following the perturbation, when comparing DT and ST conditions. Two reasons could account for the difference in their

results from those reported here. First, they reported only data from OAs that used an ankle strategy during recovery. As the increased TA amplitudes in our study were associated with subjects rising to toes during recovery, many of our OAs used an alternative recovery strategy to the more common ankle strategy. In addition, the 350–500 ms time period is sufficiently long to include cortically influenced voluntary response activation (>200 ms). In the current study, the increases in TA amplitudes were seen during the early, automatic phase of the postural response.

Alterations in performance were seen in postural and cognitive tasks under DT conditions for both Y and OAs, which indicate that the VWM task and the automatic postural response share a common attentional resource that is limited. Our results demonstrate that attentional resources used for these tasks are significantly reduced with aging, and we posit that competition for an isolated set of attentional resources can negatively affect balance under challenging postural conditions.

In summary, both Y and OAs exhibited a decrease in capacity when performing a VWM and a postural task concurrently. The general capacity theory for attention suggests that there is a finite amount of processing space available in the CNS to perform tasks and this study provides further evidence to the theory that attentional resources decline with aging. With reduced attentional processing capacity and limited postural control abilities, OAs were less able to recover and thus shifted postural strategies in DT conditions from higher frequencies of an ankle strategy to either up-on-toes or stepping strategies. However, it is possible that this shift in strategy may actually increase the risk of falls for OAs in DT situations, as previous research has shown that using a step in balance recovery requires more attentional resources than remaining in place (Brown et al. 1999).

We recommend that rehabilitation strategies to reduce falls in OAs should not be limited to physical therapy for balance control in isolation, but be practiced in DT conditions, in order to improve the ability to appropriately allocate attentional resources to balance in these complex task conditions (Silsupadol et al. 2006). Specifically, our results indicate the importance of developing DT training activities that include rise to toes and stepping strategies to help broaden the elective choices available to OAs such that they improve their ability to navigate complex postural situations within their environment to prevent a fall and avoid hospitalization or death.

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References

- Alexander BH, Rivara FP, Wolf ME. The cost and frequency of hospitalization for fall-related injuries in older adults. *Am J Public Health.* 1992; 82:1020–1023. [PubMed: 1609903]
- Arbuthnott K, Frank J. Trail making test, Part B as a measure of executive control: validation using a set-switching paradigm. *J Clin Exp Neuropsychol.* 2000; 22(4):518–528. [PubMed: 10923061]
- Bohannon RW. Comfortable and maximum walking speed of adults aged 20–79 years: reference values and determinants. *Age Ageing.* 1997; 26(1):15–19. [PubMed: 9143432]

- Brauer SG, Woollacott M, Shumway-Cook A. The interaction effects of cognitive demand and recovery of postural stability in balance-impaired elderly persons. *J Gerontol Med Sci.* 2001; 56A(8):M489–M496.
- Brown LA, Shumway-Cook A, Woollacott MH. Attentional demands and postural recovery: the effects of aging. *J Gerontol Med Sci.* 1999; 54A(4):M165–M171.
- Bugalho P, Veana-Baptista M. Predictors of cognitive decline in the early stages of Parkinson's disease: a brief cognitive assessment longitudinal study. *Parkinson's Disease.* 2013; 2013:8. Article ID 912037. 10.1155/2013/912037
- Clement G, Gurfinkel VS, Lestienne F, Lipshits MI, Popov KE. Adaptation of postural control to weightlessness. *Exp Brain Res.* 1984; 57:61–72. [PubMed: 6519230]
- Cluff T, Gharib T, Balasubramaniam R. Attentional influences on the performance of secondary physical tasks during posture control. *Exp Brain Res.* 2010; 203(4):647–658. [PubMed: 20454784]
- Cocchini G, Logie RH, Della Sala S, MacPherson SE, Baddeley AD. Concurrent performance of two memory tasks: evidence for domain-specific working memory systems. *Memory Cogn.* 2002; 30(7): 1086–1095.
- Collette F, Olivier L, van der Linden M, Laureys S, Delfiore G, Luxen A, Salmon E. Involvement of both prefrontal and inferior parietal cortex in dual-task performance. *Cogn Brain Res.* 2005; 24:237–251.
- Dault MC, Frank J, Allard F. Influence of a visuo-spatial, verbal and central executive working memory task on postural control. *Gait Posture.* 2001; 14:110–116. [PubMed: 11544062]
- Doumas M, Smolders C, Krampe RT. Task prioritization in aging: effects of sensory information on concurrent posture and memory performance. *Exp Brain Res.* 2008; 187:275–281. [PubMed: 18273609]
- Field, A. *Discovering statistics using SPSS.* 3. SAGE Publications; London: 2009.
- Folk CL, Hoyer WJ. Aging and shifts of visual spatial attention. *Psychol Aging.* 1992; 7:453–465. [PubMed: 1388867]
- Folstein MF, Folstein SE, McHugh PR. "Mini-mental state": a practical method for grading the cognitive state of patients for the clinician. *J Psychiatr Res.* 1975; 12:189–198. [PubMed: 1202204]
- Hadjistavropoulos T, Carleton RN, Delbaere K, Barden J, Zwakhalen S, Fitzgerald B, Ghandehari OO, Hadjistavropoulos H. The relationship of fear of falling and balance confidence with balance and dual-task performance. *Psychol Aging.* 2012; 27(1):1–13. [PubMed: 21707181]
- Hasher, L.; Zacks, RT. Working memory, comprehension, and aging: a review and a new view. In: Bower, GH., editor. *The psychology of learning and meditation.* Academic Press; New York: 1988. p. 193-225.
- Hernandez D, Rose DJ. Predicting which older adults will or will not fall using the Fullerton Advanced Balance Scale. *Arch Phys Med Rehabil.* 2008; 89:2309–2315. [PubMed: 18976981]
- Horak FB, Nashner LM. Central programming of postural movements: adaptation to altered support-surface configurations. *J Neurophysiol.* 1986; 55(6):1369–1381. [PubMed: 3734861]
- Horak FB, Diener HC, Nashner LM. Influence of central set on human postural responses. *J Neurophys.* 1989; 62(4):841–853.
- Huxhold O, Li SC, Schmiedek F, Lindenberger U. Dual-tasking postural control; aging and the effects of cognitive demand in conjunction with focus of attention. *Brain Res Bull.* 2006; 69:294–305. [PubMed: 16564425]
- Jennings JM, Dagenbach D, Engle CM, Funke LJ. Age-related changes and the Attention Network Task: an examination of alerting, orienting, and executive function. *Aging Neuropsychol Cogn.* 2007; 14(4):353–369.
- Jost K, Bryck RL, Vogel EK, Mayr U. Are old adults just like low working memory young adults? Filtering efficiency and age differences in visual working memory. *Cereb Corte.* 2011; 21:1147–1154.
- Kahneman, D. *Attention and effort.* Prentice Hall; Englewood Cliffs: 1973.
- Lajoie Y, Teasdale N, Bard C, Fleury M. Attentional demands for static and dynamic equilibrium. *Exp Brain Res.* 1993; 97:139–144. [PubMed: 8131825]

- Little, CE. PhD Thesis. University of Oregon; 2012. The role of attention in fall prevention—evaluation of dual task interference with postural and visual working memory tasks in young and older adults; does capacity limitation influence postural responses?.
- Logie RH, Zucco GM, Baddeley AD. Interference with visual short-term memory. *Acta Psychol.* 1990; 75:55–74.
- Logie RH, Pernet CR, Buonocore A, Della Salla S. Low and high imagers activate networks differentially in mental rotation. *Neuropsychologia.* 2011; 49:3071–3077. [PubMed: 21802436]
- Luck SJ, Vogel EK. The capacity of visual working memory for features and conjunctions. *Nature.* 1997; 390:279–281. [PubMed: 9384378]
- Macpherson JM, Horak FB, Dunbar DC, Dow RS. Stance dependence of automatic postural adjustments in humans. *Exp Brain Res.* 1989; 78:557–566. [PubMed: 2612599]
- McCollough AW, Machizawa MG, Vogel EK. Electrophysiological measures of maintaining representations in visual working memory. *Cortex.* 2007; 43(1):77–94. [PubMed: 17334209]
- Mecagni C, Smith JP, Roberts KE, O’Sullivan SB. Balance and ankle range of motion in community-dwelling women aged 64 to 87 years: a correlational study. *Phys Ther.* 2000; 80(10):1004–1011. [PubMed: 11002436]
- Nardone A, Schieppati M. Postural adjustments associated with voluntary contraction of leg muscles in standing man. *Exp Brain Res.* 1988; 69:469–480. [PubMed: 3371431]
- Nashner L, Berthoz A. Visual contribution to rapid motor responses during postural control. *Brain Res.* 1978; 150:403–407. [PubMed: 678978]
- Norman, GR.; Streiner, DL. *Biostatistics: the bare essentials.* 2. B.C. Decker Inc; London: 2000.
- Norrie RG, Maki BE, Staines WR, McIlroy WE. The time course of attention shifts following perturbation of upright stance. *Exp Brain Res.* 2002; 146:315–321. [PubMed: 12232688]
- Pai Y-C, Maki BE, Iqbal K, McIlroy WE, Perry SD. Thresholds for step initiation induced by support-surface translation: a dynamic center-of-mass model provides much better prediction than a static model. *J Biomech.* 2000; 33:387–392. [PubMed: 10673124]
- Pashler H. Familiarity and visual change detection. *Percept Psycho-physiol.* 1988; 44:369–378.
- Quinn JG. Towards a clarification of spatial processing. *Q J Exp Psychol.* 1994; 47A(2):465–480.
- Rankin JK, Woollacott MH, Shumway-Cook A, Brown LA. Cognitive influence on postural stability: a neuromuscular analysis in young and older adults. *J Gerontol Med Sci.* 2000; 55(3):M112–M119.
- Salthouse TA. The nature of the influence of speed on adult age differences in cognition. *Dev Psychol.* 1994; 30:240–259.
- Shumway-Cook, A.; Woollacott, MH. *Motor control: translating research into clinical practice.* 4. Williams & Wilkins; Baltimore: 2012. p. 166
- Shumway-Cook A, Woollacott M, Kerns KA, Baldwin M. The effects of two types of cognitive tasks on postural stability in older adults with and without a history of falls. *J Gerontol A Biol Sci Med Sci.* 1997; 52(4):M232–M240. [PubMed: 9224435]
- Silsupadol P, Siu KC, Shumway-Cook A, Woollacott MH. Training of balance under single and dual-task conditions in older adults with balance impairment. *Phys Ther.* 2006; 86(2):269–281. [PubMed: 16445340]
- Siu K-C, Chou L-S, Mayr U, van Donkelaar P, Woollacott MH. Does inability to allocate attention contribute to balance constraints during gait in older adults? *J Gerontol Med Sci.* 2008; 63A(12):1364–1369.
- Sperling G. The information available in brief visual presentations. *Psychol Monogr.* 1960; 74(498)
- Spiraduso, WW.; Francis, KL.; MacRae, PG. *Physical dimensions of aging.* 2. Human Kinetics; United States: 2005.
- Tinetti ME, Speechley M, Ginter SF. Risk factors for falls among elderly persons living in the community. *N Engl J Med.* 1988; 319:1701–1707. [PubMed: 3205267]
- Vogel EK, Machizawa MG. Neural activity predicts individual differences in visual working memory capacity. *Nature.* 2004; 428:748–751. [PubMed: 15085132]

- Wickens, CD. Processing resources in attention, dual task performance, and workload assessment. In: Parasuraman, R.; Davies, R., editors. Varieties of attention. Academic Press; New York: 1983. p. 63-102.
- Woollacott M, Vander Velde TJ. Non-visual spatial tasks reveal increased interactions with stance postural control. *Brain Res.* 2008; 1208:95–102. [PubMed: 18394592]
- Woollacott MH, Shumway-Cook A, Nashner LM. Aging and posture control: changes in sensory organization and muscular coordination. *Int J Aging Hum Dev.* 1986; 23(2):97–114. [PubMed: 3557634]

A Experimental Paradigm

B Four possible square configurations

Fig. 1.

a Subjects gazed at the screen in front of them when performing the cognitive task and manually depressed buttons during both ST and DT conditions. Neutral posture was maintained and restored naturally; if step(s) were taken, subjects resumed the initial position traced on the force plates. No constraint was placed on subjects to maintain neutral posture without moving their feet. **b** Four possible square configurations

Fig. 2.

a Young and OAs demonstrated a significant decline in VWM capacity with increased postural challenge. Legend: YAs ** sit versus perturbation ($p < 0.01$). OAs * represents sit versus stand ($p < 0.05$), *** sit versus perturbation ($p < 0.001$), and ** (red on figure) “expectation” versus perturbation ($p < 0.01$). **b** The drop in VWM capacity between sit and “expectation” and sit and perturbation was significantly greater for OAs ($p < 0.001$) but not YAs ($p < 0.063$). Error bars represent SE of the mean (SE)

Fig. 3.

a Older adults showed a significant increase ($p < 0.05$) in the mean number of trials in which step(s) were taken between ST and DT conditions, whereas YAs did not ($p < 0.177$). **b** The mean number of steps taken during ST and DT conditions is compared between the OA group and the five frail OAs included in the data collection. *Error bars* represent SE of the mean (SE)

Fig. 4.

A significant increase was seen in the mean number of trials in which OAs used rise to toes ($p < 0.05$) as part of their postural recovery pattern in DT versus ST conditions, whereas none was seen in YAs ($p < 0.199$). *Error bars* represent standard error of the mean (SE)

Summary of neuropsychological and physical test scores (group means and SDs), with normative guidelines from the literature (Arbuthnott and Frank 2000; Bugalho and Veana-Baptista 2013; Bohannon 1997)

Table 1

Test	Young adults	Older adults	Frail older adults	Established guidelines		Cut off related to decline in function
				Normal		
Trail Making Test (TMT)—Part A (s)	19 ± 4 ^{***}	29 ± 8	40 ± 8	YA: 27.4 ± 9.6 OA: 47.2 ± 17.9	>78	
TMT—Part B (s)	41 ± 12 ^{***}	59 ± 19	111 ± 40	YA: 58.7 ± 15.9 OA: 119.4 ± 50.2	>273	
Mini-Mental State Examination (MMSE) (30/30)	Not tested	29 ± 2	27 ± 2	24–30 (no cognitive impairment)	22 (0–2 yrs school) 24 (3–6 years school) 27 (7 years school)	
Fullerton Advanced Balance (FAB) Score (40/40)	39.1 ± 0.7 ^{***}	34.8 ± 2.5	23.8 ± 1.6	25–40	25 (prone to have a fall)	
Comfortable gait speed (m/s)	1.2 ± 0.2	1.07 ± 0.2	0.89 ± 0.11	YA: 1.4 ± 0.2	OA: 1.3 ± 0.2	

***
 $p < 0.001$ Interaction between clinical test and age group—YAs versus OAs ($F(2,65) = 47.51$, $p < 0.001$, $r = 0.6$), post hoc Bonferroni correction

Table 2
Summary of the experimental protocol and identification of trial groupings used in the data analysis

Postural condition	Single-task (ST)	Dual-task (DT)	Analysis
Control: sitting	Change-detection task (set size 2, 4, and 6 squares)	NA	Correct and incorrect responses from the 90 trials were collated and used to calculate the estimate of visual working memory capacity for each subject (K-Score) (see formula in text)
Isolated stance	No change-detection task	2 squares* 30 trials 4 squares* 30 trials 6 squares* 30 trials NA	NA NA As above
Perturbation (pert.) of the support surface	No change-detection task	Change-detection task (set sizes 2, 4, and 6 squares) Change-detection task (set sizes 2, 4, and 6 squares) Trials 1–14 were ST, trials 15–116 DT, and trials 117–127 ST NOTE: 1 forward pert. trial was included among the ST trials before and after the 90 DT trials and 11 forward pert. trials were randomly presented among the DT trials	Trials 1–3 were eliminated to account for learning Trials 10–14 represented the ST postural response Trials 15–19 represented the DT postural response K-Score estimate for each subject was calculated using the set size responses from the 90 DT trials Stepping strategy: all 20 ST and 90 DT trials were evaluated Up-on-toes: trials 10–14 and 117–121 represented overall ST performance. Trials 15–19, 60–65, 112–116 represented overall DT performance
Isolated stance intermixed with perturbation of the support surface	No change-detection task	NA	K-Score estimate was calculated using set size responses from the approximate 1.061 ± 39 trials presented randomly between the 90 perturbation trials

Table 3

Summary of the number of subjects who either stepped or used rise to toes as part of their postural recovery pattern periodically across the 115 trials included in the experimental paradigm

Group	Condition	Behavioral postural measure	Percentage of subjects stepped	Mean number of trials
YA	ST	Step	9 % (3/33)	0.1 ± 0.4
YA	DT	Step	18 % (6/33)	0.4 ± 1.3
YA	ST	Rise to toes	15 % (5/33)	0.5 ± 1.3
YA	DT	Rise to toes	18 % (6/33)	0.7 ± 2.3
OA	ST	Step	57 % (17/30)	1.7 ± 2.4
OA	DT	Step	50 % (16/30)	3.4 ± 5.4
OA	ST	Rise to toes	47 % (14/30)	2.4 ± 3.3
OA	DT	Rise to toes	57 % (17/30)	3.4 ± 4.7